

THE IMPACT HISTORY OF THE MOON

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The bombardment history of the Earth-Moon system has been debated since the first recognition that the circular features on the Moon may be impact craters. Because the lunar impact record is the only planetary impact record to be calibrated with absolute ages, it underpins our understanding of geologic ages on every other terrestrial planet. One of the more remarkable results to come out of lunar sample analyses is the hypothesis that a large number of impact events occurred on the Moon during a narrow window in time approximately 3.8 to 4.1 billion years ago (the lunar “cataclysm”). Subsequent work on the lunar and martian meteorite suites; remote sensing of the Moon, Mars, asteroids, and icy satellites; improved dynamical modeling; and investigation of terrestrial zircons extend the cataclysm hypothesis to the Earth, other terrestrial planets, and possibly the entire solar system. Renewed US and international interest in exploring the Moon offers new potential to constrain the Earth-Moon bombardment history. This paper will review the lunar bombardment record, timing and mechanisms for cataclysmic bombardment, and questions that may be answered in a new age of exploration.

The IMPACT HISTORY OF THE MOON

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ABSTRACT

Here's the abstract of the paper.

1. INTRODUCTION

The bombardment history of the Earth-Moon system has been debated since the first recognition that the circular features on the Moon may be from impact processes [1]. In the early 1970's, ^{40}Ar - ^{39}Ar and U-Pb isotopic analyses of Apollo 15, 16 and 17 rocks [2, 3] revealed surprising, widespread isotopic disturbances at ~3.9 Ga. Argon and lead loss was attributed to impact metamorphism of the lunar crust in a brief pulse of time (<200 Myr) in what was called the "lunar cataclysm." Recently, lunar impact history has been revived as a topic of debate [4, 5], fueled by renewed interest in radiometric dating of lunar and meteoritic materials and increased capability for large dynamical simulations. The NASA/NRC decadal survey underscored the need to understand the late heavy bombardment, as the lunar crater record is the only one to be pinned to radiometric ages and it forms the basis for our understanding of crater counts on every other terrestrial planet.

An anomalous period of increased bombardment around 3.9 Ga – 600 Myr after solar system formation

A post-Apollo view of a dynamic solar system

Precise ages of impact-melt samples

Large numerical simulations of planet formation & migration

Catastrophe – 1,700 craters on the Moon / 22,000 impact craters on the Earth

Catalyst – delivery of 1023 g of asteroidal/cometary material to the Earth, including C, H₂O, and reduced species

Cauldron – impact-generated hydrothermal systems may be niches

Crucible – extreme environments affect evolutionary paths

2. LUNAR SAMPLE AND GEOLOGIC FEATURE AGES

Radiometric dating of lunar impact-melt rocks forms the backbone of the lunar cataclysm hypothesis. The returned Apollo and Luna sample collections contain impact melt samples as rocks, clasts in breccias, and soil fragments. A histogram of precise age determinations of Apollo and Luna impact-melt rocks [6-8 and many others] (Fig. 1), shows the characteristics of the classic formulation of the lunar cataclysm hypothesis: a sharp peak at 3.9 Ga, a steep decline after 3.9 Ga perhaps only 20-200 Myr long, and few, if any, positively identified rocks of impact origin prior to ~4.0 Ga. The stochastic nature of lunar meteorite launch events and the feldspathic content of several lunar meteorites indicate that they represent a more random

sampling of the lunar surface than do the Apollo and Luna samples. Impact-melt clasts in these rocks [9-11 and references therein] show the same apparent age cutoff at 4.0 Ga though their ages extend ~500 Myr later. Glass spherules in lunar soil are formed by smaller impacts that occur even after formation of the large basins; these samples show a correspondingly even distribution throughout lunar history [12, 13], but even these samples have an apparent cutoff at 4.0 Ga.

Geological associations between lunar samples and impact basins (or other features) puts absolute ages on several of the major lunar basins [14], showing that five large basins formed on the Moon within 200 Myr.

3. GEOCHEMISTRY OF LUNAR IMPACT MELT ROCKS

Form distinct groups in composition, texture, petrology
Reflect distinct impactor composition that formed them

A counterargument [15, 16] says that all, or nearly all, the 3.9-Ga impact melt rocks are products of a single event, the Imbrium basin-forming impact. It is still a matter of debate whether this hypothesis can accommodate the multiple groups of impact melt that are resolvable from each other in age [6, 7, 17] and in trace-element chemistry [18-20].

Even if Imbrium were solely responsible for blanketing the nearside with KREEPy 3.9-Ga impact melt rocks, this material does not cover the entire moon and feldspathic rocks should record the bombardment of the lunar highlands either distant from or prior to formation of Imbrium.

4. ALTERNATIVE EXPLANATIONS AND COUNTERARGUMENTS

The lack of impact-melt rocks older than 3.9 Ga can be interpreted either as evidence that there was a low flux of impactors prior to ~3.9 Ga [4], creating few impact melt rocks, or as evidence of a very high flux [21, 22] that radiometrically reset and/or destroyed the lunar crust (the “stone wall” effect). If the flux were much lower, then the apparent spike in impact rate would be a true “cataclysm.” If the flux were much higher, then the increased flux could be viewed as simply a bump or inflection on a generally declining post-accretionary impact rate. Unfortunately, there is little recognizable pre-Nectarian geology for crater counting, stratigraphy, or association with rock ages. Mass constraints on the amount of material needed to create the large lunar basins appears to support a low pre-Nectarian flux [23]. The stone wall effect cannot be completely true, as many non-impact, igneous lunar rocks have ages up to 4.45 Ga, but a variation of this argument [24] postulates that material stored deep in the crust is occasionally excavated by large impacts, providing old anorthositic and plutonic rocks to be sampled at the surface. The relative volume of plutons and the mechanics of large-scale regolith development are largely unconstrained, and more work needs to be done on this scenario [25].

5. EFFECTS AND EVIDENCE ON OTHER TERRESTRIAL PLANETS

That the impact flux history of the Moon should map onto the other terrestrial planets is debatable, depending on the actual dynamics of the responsible impactor populations [30]. Radiometric ages in ordinary chondrites and HED meteorites [31] peak around 3.9 Ga but are relatively spread out and ages older than 3.9 Ga are common. The sharp peak, only 200 Myr long, in the lunar rock age distribution that defines the cataclysm is not well mirrored in the meteorite data. In particular, the sharply declining cratering rate on the Moon after 3.9 Ga is not reproduced in the meteorite data, where common reset ages persist for another ~ 0.5 Ga, until later than 3.4 Ga. Martian meteorite ALH 84001 crystallized at 4.50 Ga but was altered by fluid and shock-metamorphic processes. Carbonates in this rock have ages coincident with the Ar-Ar shock-degassing age of 3.92 ± 0.04 Ga [32, 33]. The inferred age of Mercury's Caloris basin is 3.9 Ga, based on crater-counting using the lunar flux [34].

The oldest terrestrial rocks are ~ 3.9 Ga [e.g. 26] metasediments, implying that crustal formation, erosion, and sedimentation were operative at that time. These rocks also contain tungsten isotopic anomalies [27] that might record unusual extraterrestrial contributions and the earliest isotopic evidence of life [28]. In the classic cataclysm scenario, fifteen impact basins with diameters ranging from 300 to 1200 km were produced on the Moon during the Nectarian and Early Imbrian periods [29] accompanied by ~ 1700 impact craters with diameters larger than 20 km. Because the Earth has a larger gravitational cross-section than the Moon, the number of impacts occurring on Earth would have been 1-2 orders of magnitude larger than on the Moon [5], implying that $\sim 22\,000$ craters were created on the Earth, including tens of basins larger than 1000 km across. A heavy bombardment at this time must have deeply affected the terrestrial biosphere and lithosphere.

Mercury

Using lunar crater counts on well-dated mare surfaces (Neukum et al. 2001), Mercury's Caloris basin is same age as the Moon's Orientale basin - 3.8 Ga
MESSENGER mission arrives in 2010

Mars

ALH84001 (4.51 Ga) has Ar-Ar shock age of 3.92 Ga (Turner et al. 1997), carbonates deposited by water at 3.92 Ga (Rb-Sr, Borg et al. 1999)
MER is ongoing, MSL lands 2011, MSR?
New Lapen results here
Asteroids – lots of new stuff here from Bogard, me, Swindle.

The Earth

6. POSSIBLE CAUSES

The total mass necessary to create all of the late lunar basins and associated smaller craters is 10^{21} - 10^{22} g [23]. Delivery of this much material at this time requires modification of our current views of solar system formation and evolution. While it is accepted that the early solar

system accreted violently, through collision, breakup, and accretion of many protoplanets, this episode was largely over by the time the Moon formed. Sweep-up of accretional leftovers from the formation of the solar system and of the Moon is rapid (10-100 Myr) [35, 36]. Breakup and delivery of a main-belt asteroid [37] requires breakup of a Ceres-sized body, which is dynamically unlikely at 3.9 Ga and should leave an observable asteroid family. Late formation of Uranus & Neptune [38] could cause migration of Jupiter and Saturn and resonance sweeping through the main asteroid belt. Even if all the giant planets formed at the same time, rapid migration of the giant planets would destabilize both the Kuiper belt and main asteroid belt [39], sending showers of comets and asteroids toward the center of the solar system. Models of the possible existence of a fifth terrestrial planet [40] between Mars and main belt show that it could become unstable after 600 Myr and make excursions into the main asteroid belt before hitting the sun. Trace element compositions of lunar impact melts [41] may argue that the large lunar basins were produced by asteroids rather than comets, which might help further constrain dynamical modeling.

Nice Model

Strom and Malhotra results

Cuk Gladman Stewart paper: We show that morphologically fresh (class 1) craters on the lunar highlands were mostly formed during the brief tail of the cataclysm, as they have absolute crater number density similar to that of the Orientale basin and ejecta blanket. The connection between class 1 craters and the cataclysm is supported by the similarity of their size-frequency distribution to that of stratigraphically-identified Imbrian craters. Majority of lunar craters younger than the Imbrium basin (including class 1 craters) thus record the size-frequency distribution of the lunar cataclysm impactors. This distribution is much steeper than that of main-belt asteroids. We argue that the projectiles bombarding the Moon at the time of the cataclysm could not have been main-belt asteroids ejected by purely gravitational means.

7. CONTINUING TO TEST THE HYPOTHESIS

The lunar cataclysm hypothesis continues to be tested by searching for evidence of impact events in various materials. One way to anchor the early end of the lunar flux would be to directly sample the impact-melt sheet of a large lunar basin distant from Imbrium. The South Pole-Aitken basin, with a diameter of 2000 km, is the stratigraphically oldest lunar basin and probably created more impact melt than all other lunar craters combined. Though no South Pole-Aitken basin impact-melt rock has been positively identified in the Apollo, Luna, or meteorite collections, a large amount of melt probably still resides on the basin floor and could be directly sampled by a robotic mission [42].

Understand sample collection and sample bias on planetary and terrestrial surfaces

What does each sample set represent?

What other sample sets may contain information?

How many samples are required for statistical significance?

What are the differences between the lunar surface and other locations?

Relative impact velocity

Impact-melt production in crater events
Sampling rate
Further compositional grouping
Trace elements of sample sets
Fingerprinting the impactors
Potential fractionation processes
3-D regolith modeling
Fate of old impact melt sheets, volumetric importance
Pin down one large, old basin age - SPA

8. CONCLUSIONS

Impact-melt sample groups tied to individual impact events based on major, minor, and trace elements, geologic interpretation
Multiple different impact-melt groups from the Apollo landing sites are 3.9 Ga, tied to 5 large basins plus other craters?
Multiple impacts into feldspathic terrain 4.0 to 3.5 Ga
Multiple impacts in regolith breccias from Vesta 3.6 to 4.0 Ga
Very high or very low flux before 4 Ga?
Diverse approaches to further testing exist and are an opportunity for both the planetary and terrestrial communities

9. REFERENCES

FIGURES

A. ^{40}Ar - ^{39}Ar age histogram of lunar impact-melt rocks.

The Impact History of the Moon

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The Lunar Cataclysm Hypothesis

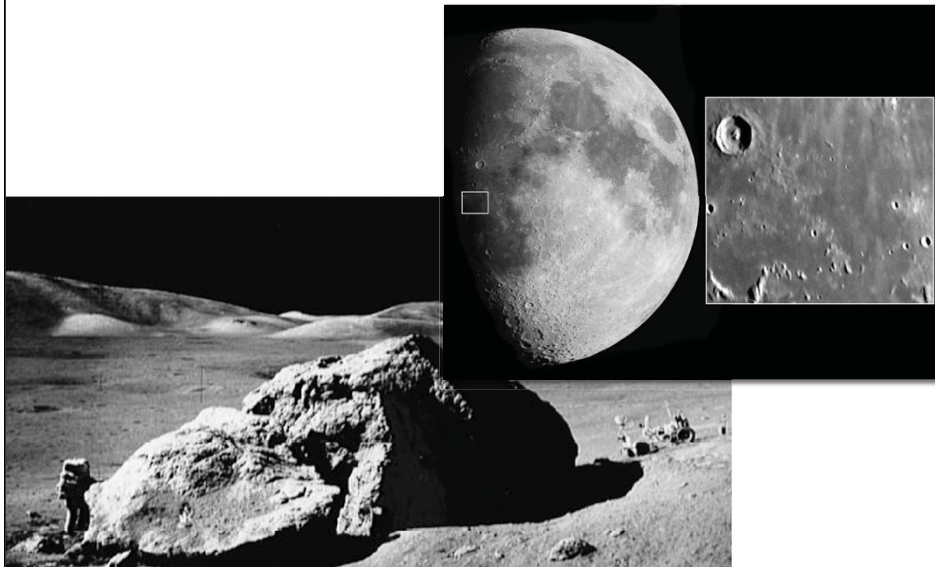
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Planetary impact materials

- Impact process is most akin to an explosion - impactor is vaporized, target is shocked, melted, comminuted, redistributed
- Metamorphosis (combination of temperature and time) separates parent species from daughter; resets isotopic clock to time of impact
- Must understand rock petrogenesis (major- and trace-element composition, mineralogy, texture, geologic association) in order to interpret ages

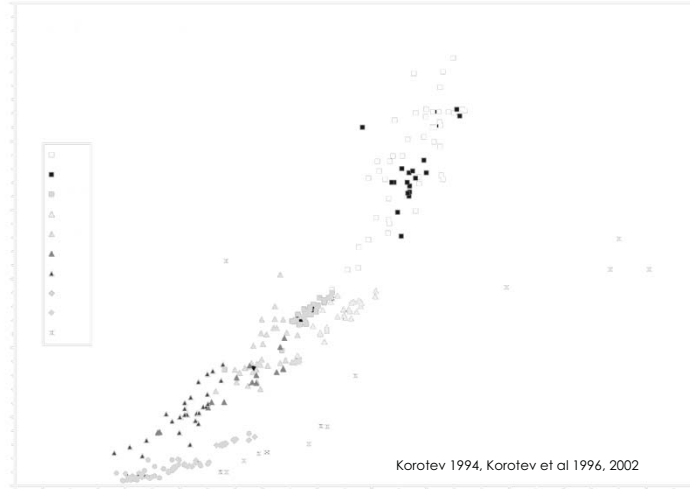
Impact-melt rocks

- Geologic association with specific craters and basins



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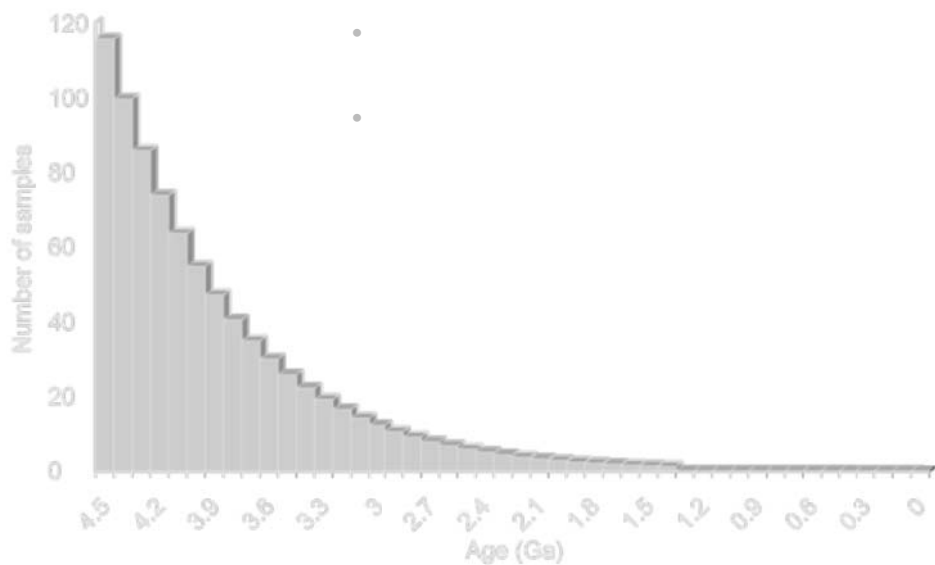


Impact melt rocks

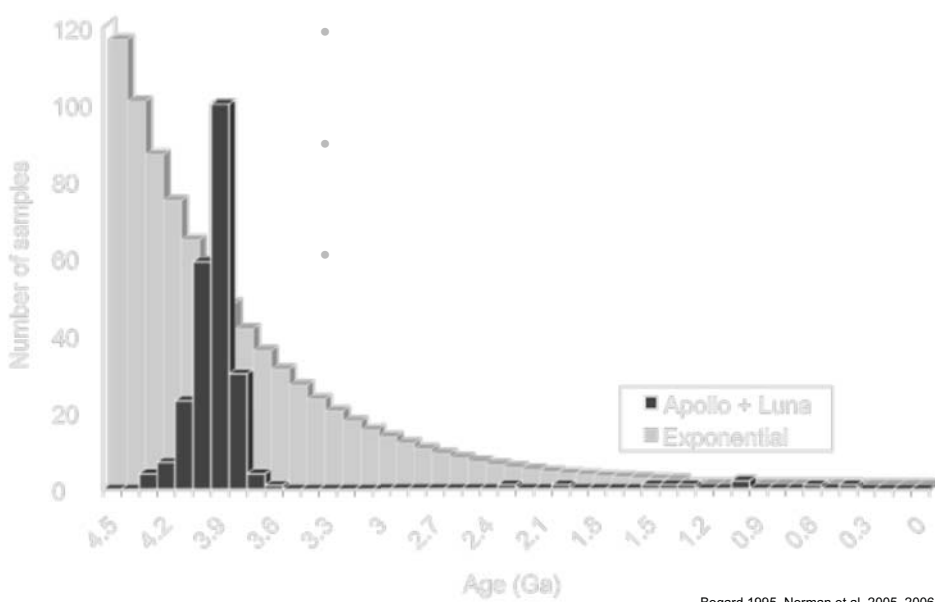
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- Form distinct groups in composition, texture, petrology
- Reflect distinct impactor composition that formed them

Kring and Cohen 2002, Norman et al. 2002, James et al. 2006, Puchtel et al. 2007

Impact rock geochronology

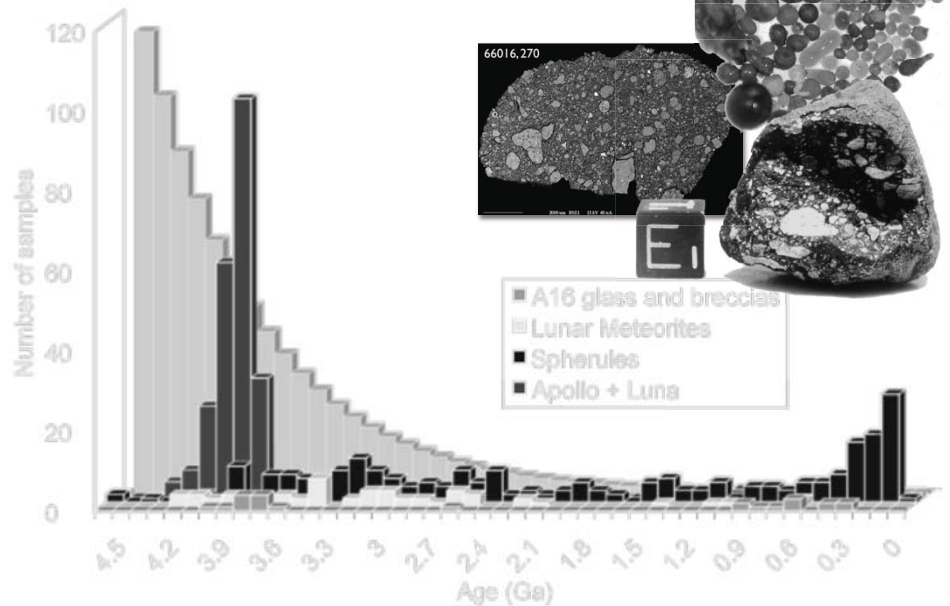


Apollo + Luna impact ages



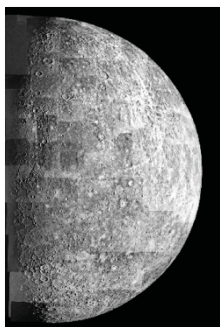
Bogard 1995, Norman et al. 2005, 2006

Other lunar samples?



Culler et al 2000, Cohen et al. 2000, 2005, 2007, 2008, Fernandes et al. 2000, 2004, Daubar et al. 2002, Zellner et al. 2003, 2005, Levine et al 2005

The terrestrial planets?

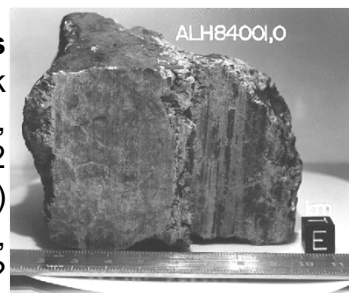


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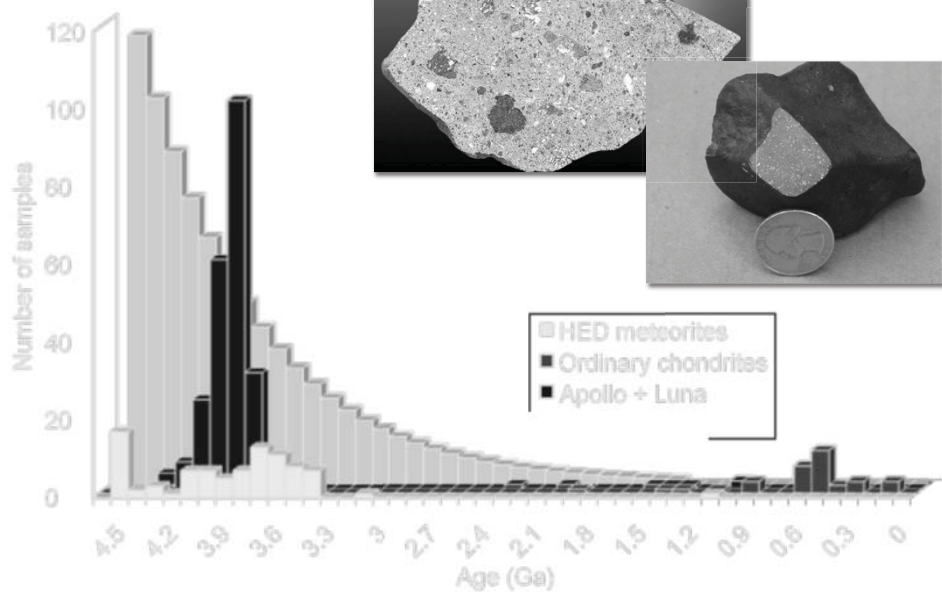
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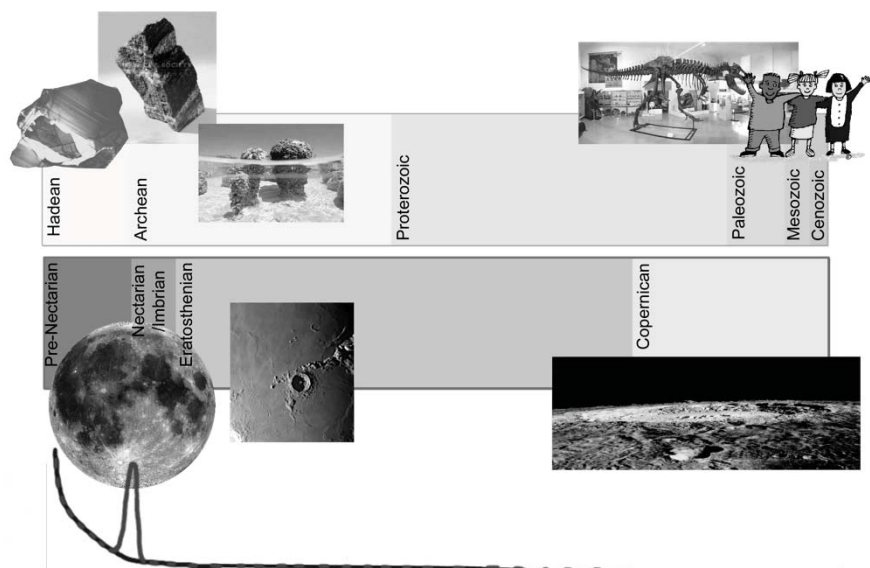


Asteroids?



Bogard 1995 and references therein; Bogard and Garrison 2003, Cohen et al. 2007

The Earth?



Further Testing

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A Lunar Cataclysm...?



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